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TILTMETER INSTRUMENTATION FOR DEEP HOLE OPERATION

SEMI-ANNUAL TECHNICAL REPORT

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Arthur D. Little, Inc.

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SEMI-ANNUAL TECHNICAL REPORT

15 June 1971 through 15 December 1971

TILTMETER INSTRUMENTATION FOR DEEP HOLE OPERATION

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Arthur D. Little, Inc.

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13. ABSTRACT

The first of the deep-hole tiltmeter systems developed under the present contract was completed and is under tests in a shallow borehole in a stable rock formation at Bedford, Massachusetts.

The performance of the system was found to be on the whole satisfactory and it continues to be satisfactory after more than 3000 hours of continuous operation in the borehole. Nevertheless, a few unexpected problems were encountered during the tests. A 'tilt noise' caused by thermal convection in the water-filled borehole was found to interfere with recording at low signal levels. Apparent drift of the zero setting was observed when the downhole package was mechanically decoupled from the cable. The present data logging system, when operated at sampling rates slow enough to permit long-term unattended operation lacks the capability of recording randomly occurring events of short duration. Most of these problems have been resolved and modifications will be made in the present and forthcoming units.

A new site for a tectonophysical application of the DBT system was suggested in addition to the sites originally considered at the outset of the present program. This site is in the vicinity of the Stone Canyon seismological and strain recording station operated by EML/NOAA approx. 10 miles S of Hollister, Calif. The original application planned for the deep-hole tiltmeter instrumentation was for measuring and continually recording changes in the strain field of deep-seated artificial stress sources (e.g., injection wells). The proposed new site is on an active segment of San Andreas fault and thus offers the opportunity for using the deep-hole tiltmeter system for studying the changes in tilt and strain in relation to fault movements of natural origin.

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I. SUMMARY

The first of the deep-hole tiltmeter systems developed under the present contract was completed and is under tests in a shallow borehole in a stable rock formation at Bedford, Massachusetts.

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II. DEEP-HOLE TILTMETER SYSTEM DBT-1

The complete system includes the downhole instrument package, the uphole control and data acquisition electronics and the seven-conductor, double-armored cable (presently only a temporary cable of 250 ft length is available). The DBT-1 system is shown in Figure 1.

The downhole package is 105 in. long, 5.25 in. maximum diameter at holelock shoulders and it weighs approximately 300 pounds. It is connected to the cable (Vector Cable Co. type 7-46NT) by an electro-mechanical connector permanently fixed and molded to the cable.

The biaxial tiltmeter module with its downhole electronics was calibrated in the laboratory at temperatures from 25 to 125°C. For a limited temperature range (approximately 25 $\pm$10°C) the calibration equations are linear, of a form

$$\theta = a + bV + c(t-25),$$

where θ is the tilt in μ radians, V the output voltage in volts and t the temperature of the borehole package in °C. The constant a may be set equal to zero or any arbitrary value by initial leveling. Constants b and c have the following values:

channel 2 (Y-tilt): $b = 150$, $c = 1.6$
channel 3 (X-tilt): $b = 210$, $c = .85$

The downhole temperature is measured by a thermistor circuit over channel 5 having the following calibration equation:

$$t = 3.0 + 50V \quad (°\mathrm{C, volts}).$$

The electronics were constructed exactly as described in the preceding Annual Report. The uphole unit is completely contained in a 15 x 22 x 28 in^3. steel cabinet including the digital printer. A separate cabinet contains a paper tape punch operating in parallel with the printer. The punch generates an 8-bit, parallel word tape that can be read and further processed using a standard teletype computer terminal. Several programs for tabulating, plotting etc., were written for reduction of data. A view of the uphole electronics installed in a trailer at the test site is shown in Figure 2.

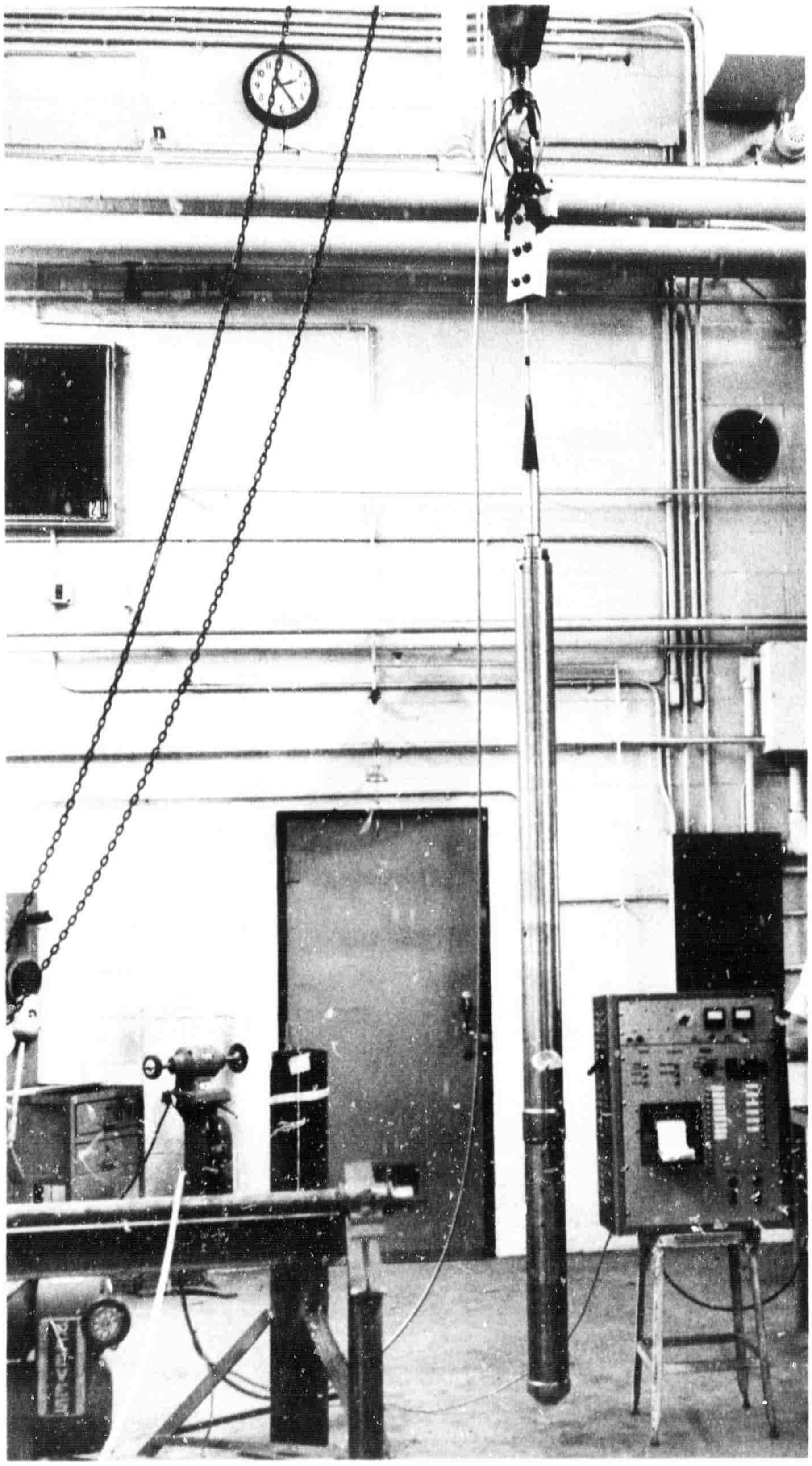

FIGURE 1 View of the Complete Deep-Hole Tiltmeter System DBT-1

FIGURE 2 Control Electronics and Paper Tape Punch in Trailer At Test Site

III. FIELD TESTS AT BEDFORD, MASSACHUSETTS

Field tests of the complete DBT-1 system were started in mid-August 1971. The purpose of the tests was to check the performance of all parts of the system under field conditions and to determine the typical drift rates under stable ground conditions.

For this purpose a borehole was drilled in bedrock (granitic gneiss) at Bedford, Massachusetts, adjacent to a crustal tilt network operated by AFCRL; drilling was completed on 30 April 1971. The borehole is 115 ft. deep and is cased to a depth of 104 ft. with 7 in./17# steel casing of 6.5 in. I.D. The overburden is only approximately one foot deep. The casing was cemented to the rock over its entire length and the top 5 ft. are protected by a 10 in. diameter steel pipe cemented into the rock. The borehole became filled with water which stands to about 12 ft. below the surface.

The temperature in the borehole is presently around 14°C at the top of the water level and it decreases to a minimum of approximately 10°C at a depth of 38 ft. Below this point it increases by approximately 0.5°C to the bottom. This corresponds to a gradient of approximately 21°C/km. When the downhole package is in operation it generates approximately 18 watts of heat and the gradient above it increases to approximately 45°C/km. Gradient of this magnitude exceeds the critical value for Hales' convective instability (see, e.g., P. E. Gretener; Geophysics, Vol. 32, p. 727, 1967). For the borehole of present radius (8.25 cm) and using appropriate values for viscosity, diffusivity and volume expansion of water, the critical gradient calculated by Hales' equation is 32°C/km. Therefore, with the downhole package operating the water column in the borehole should be in the unstable region. The instability was actually first recognized by excessive "tilt noise" and subsequently confirmed by direct recording of temperature fluctuations with a thermistor probe.

The DBT-1 tiltmeter was installed in the borehole on 17 August 1971 using a 15 ft. high tripod erected over the wellhead and a 3-ton truck to back off the cable over a pair of pulleys (Figure 3). When the lower end of the downhole package reached the predetermined depth (100 ft) the holelock was actuated from the control unit and a clamp was fixed on the cable, approximately one foot above the rim of the casing. The cable was then allowed to slacken until the clamp rested on the casing and the tripod and pulleys were removed.

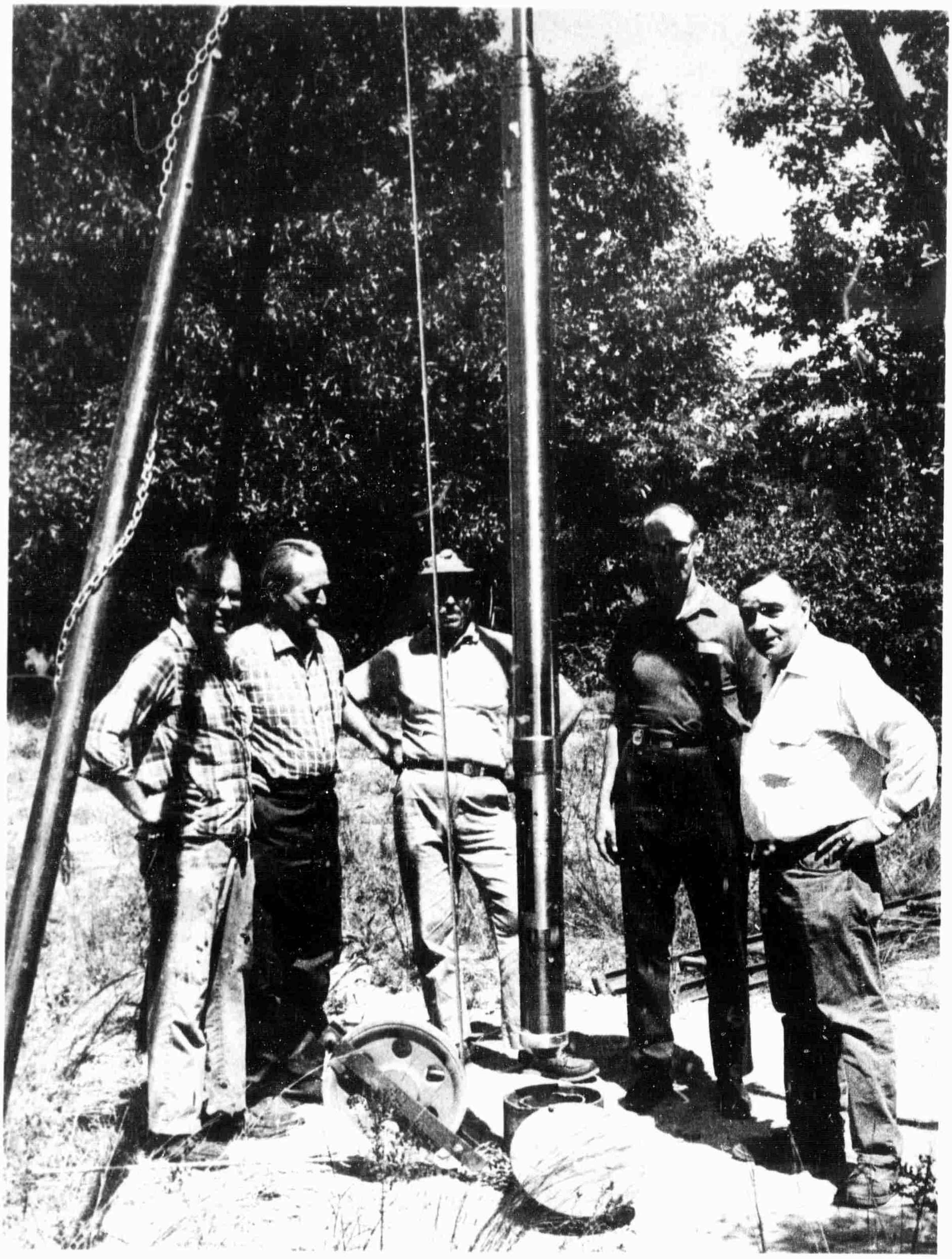

FIGURE 3 Deep-Hole Package Being Installed in the Test Borehole at Bedford, Massachusetts

The tiltmeters were then leveled from the control panel and recording started; at first on 10 minute and later on one-hour printout periods. A plot of the first three days of recording is shown in Figure 4. After the initial settling period (approximately one day) the mean values of the two tilt components became reasonably steady. The drift rate, estimated from continual recording over the following four weeks was approximately 3 μrad/mo. for channel 2 (Y-tilt) and approximately zero for channel 3 (X-tilt).

During all this time both channels showed random fluctuations as large as approximately 5 μrad (p-p). The origin of this "tilt noise" was traced down to the convective instability of the water column in the borehole discussed above. Simultaneous recording of water temperature and tilt showed fluctuations of very similar frequency spectrum with dominant periods between 300 to 800 sec (3.3 to 1.25 mHz). The amplitude of water temperature fluctuations was too small to account for the observed noise as a direct effect of temperature on tilt sensors. Since their temperature coefficients are of the order of 1 μrad/°C the temperature would have to vary by several degrees while, in fact, the recorded fluctuations seldom exceeded 0.1°C (p-p). Similarly, estimates of thermoelastic strains of the borehole casing were found to be too small to account for the observed large tilt fluctuations.

Our conclusion was, therefore, that the holelock did not hold the downhole package firmly enough to prevent it from moving slightly as its top was subject to forces exerted by the cable swaying by the effect of water convection. This surmise was confirmed eventually by eliminating the rigid coupling between the cable and the top of the downhole package. This was done by inserting a 10 ft. length of unarmored, flexible, 7-conductor cable between the end connector of the armored cable and the receptacle at the top of downhole package. Two parallel steel chains of 6 ft. length were provided to support the downhole package from the end of the armored cable while it was being installed in the borehole. After the holelock was locked and the cable slackened at the top the downhole package became substantially decoupled from the cable.

The effectiveness of this arrangement can be seen from Figure 5 which is a computer plot of tilt recording between 13 and 16 October 1971. Comparing with the record of Figure 4 we see that the noise was substantially reduced but not eliminated entirely.

An unexpected and undesirable side effect of decoupling from the cable was an increase in drift rate. The drift rate in both tilt components became as large as approximately 15 μrad/mo. shortly after installation and even after three weeks it decreased only to 9.6 μrad/mo. in the Y component and to 12 μrad/mo. in the X-component. Since no change was made in the downhole package we conclude that the increased drift results from a slow shift of the package in the borehole casing.

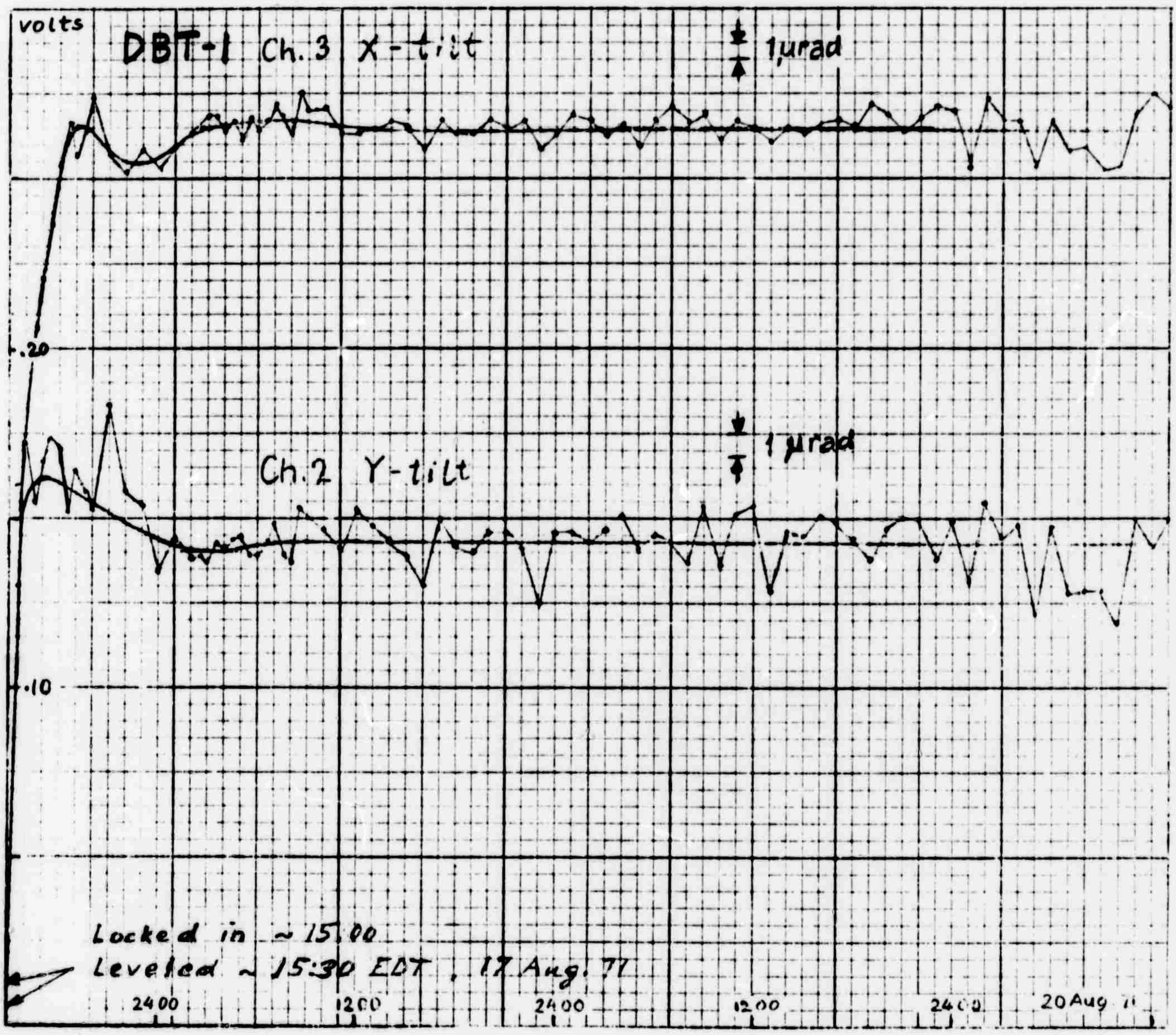

FIGURE 4 Recording of Tilt After Initial Installation in 100 ft. Borehole (large tilt noise)

Consequently, we plan to make appropriate modifications of the present hole locking method to insure more stable contact with the casing.

Another useful experience gained during this test period related to the mode of data acquisition. On 15 December 1971, a large transient tilt signal was recorded at 0400 EST (0900 GT) as shown in Figure 5. This was recognized as the response of the instrument to the surface wave train from the Kamchatka Peninsula earthquake ($m \approx 7.6$) which was recorded (insert in Figure 5) by one of our (surface) tiltmeters being tested in the Harvard Observatory vault. At the one-hour sampling period the recording of this event by the DBT-1 system was rather unsatisfactory and, in fact, fortuitous. It would have been much more useful had we been operating at a faster sampling rate (10 min. or 1 min intervals), or having at least one of the channels on a continuous (analog) recorder. We plan to modify the electronics so as to permit recording one channel continually while sampling all other channels periodically.

Another experiment performed during the tests at the Bedford site was an attempt to eliminate the convective instability in the borehole altogether. Following the practice adopted earlier by G. H. Cabaniss of AFCRL we filled the borehole with a 3.5 percent solution of a drilling mud additive ("Polygel"). In this concentration the additive increases the viscosity of water by a factor of approximately 100 and thus suppresses the convection. In the Hales' equation viscosity appears directly as a factor in the dominant term. Hence, the critical gradient should be raised in our case from 32 to 3200°C/km.

The results obtained with the Polygel treatment were highly promising as can be seen from the recording in Figure 6. The Polygel treatment was actually tried before the cable decoupling method was put in operation. The disadvantage of the Polygel treatment is that it is not permanent and needs to be repeated at intervals of the order of a month.

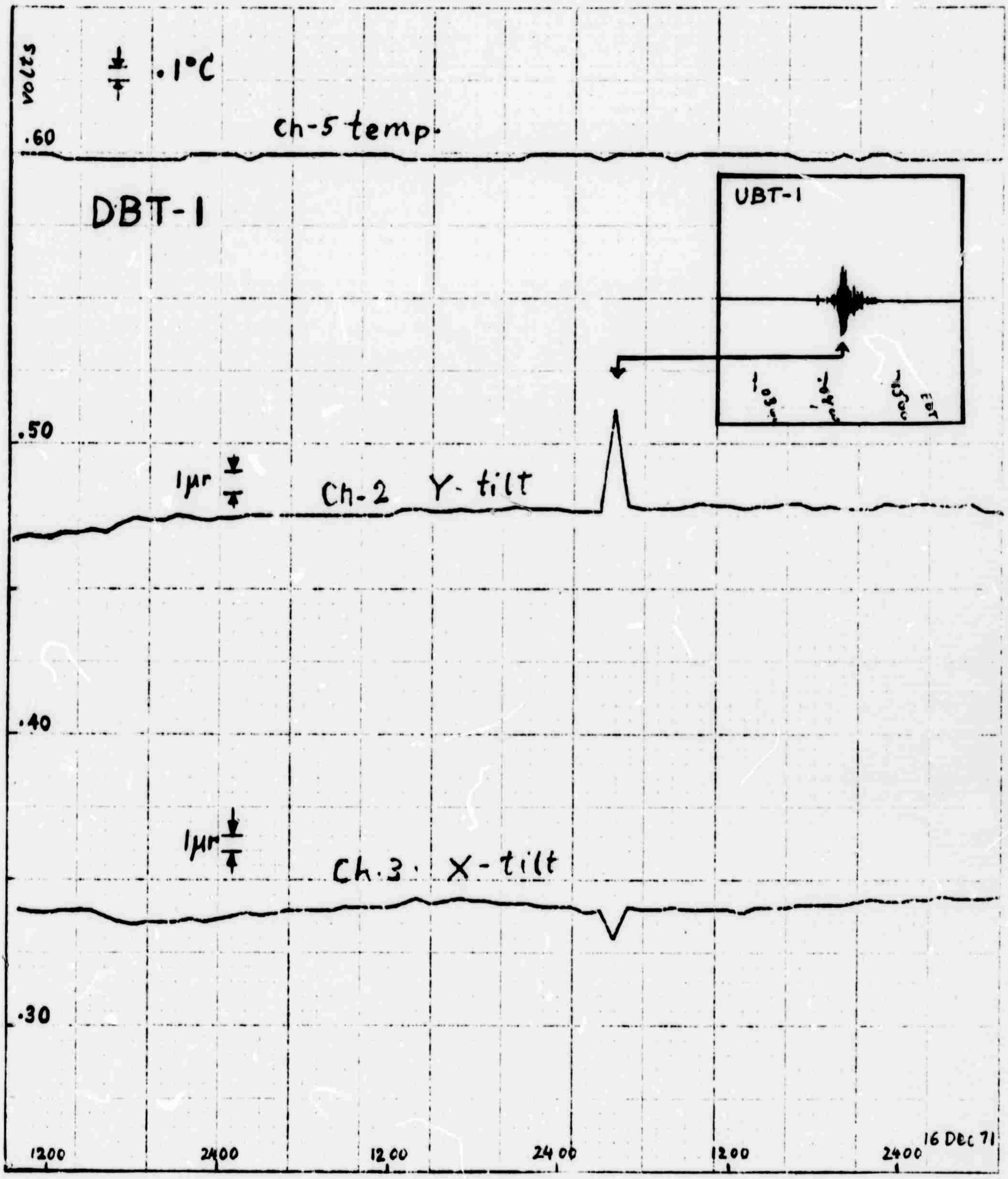

FIGURE 5 Recording of Tilt With Downhole Package Mechanically Decoupled from Cable to Reduce Noise. The seismic event is the earthquake at Kamchatka Peninsula, 15 December 1971, m=7.6.

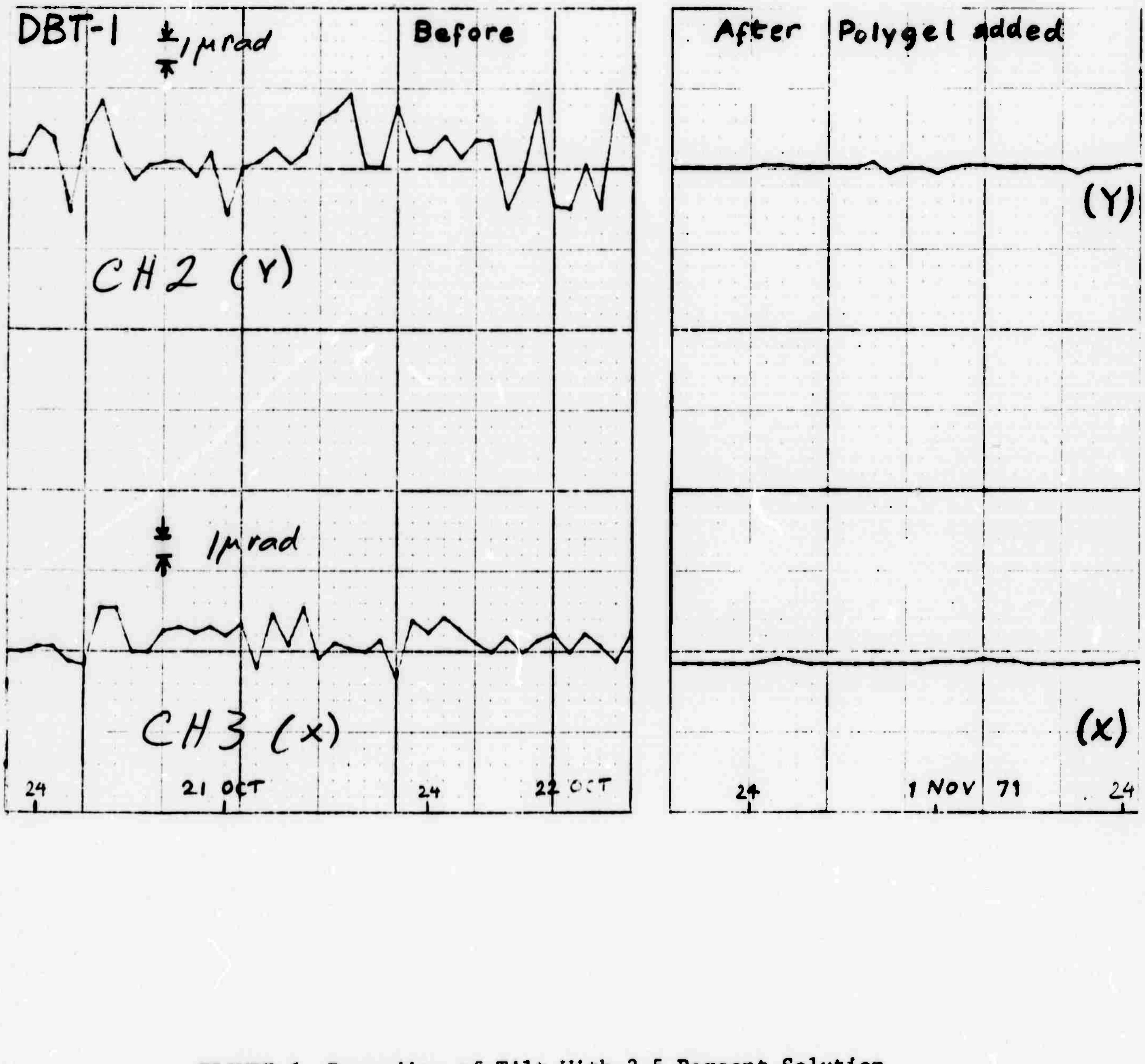

FIGURE 6 Recording of Tilt With 3.5 Percent Solution of Drilling Mud Additive (Polygel) in Borehole

IV. WORK IN PROGRESS

Tests in the borehole at the Bedford site will be continued at least through January 1972. Two more experiments are scheduled for the DBT-1 system; one is the addition of a cable stabilizer to the present setup and the other is to replace the downhole package from the 100 ft. level to rest at the bottom of the borehole. After the conclusion of the tests the DBT-1 system will be disassembled for checks and modifications. A horizontal assembly fixture specially constructed for the purpose will be used instead of the original vertical assembly technique which was difficult and time consuming.

Two more UBT units are under construction. They will be equipped with tilt sensors of higher sensitivity and will incorporate other modifications discussed in Section III.

The DBT-1 system (and the DBT-2, later) will be prepared for shipment to the test site at Stone Canyon. The DBT-3 system will be eventually prepared for use in an oil field experiment at an as yet unspecified site. Negotiations regarding alternate experiment sites will be continued.